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Volcaniclastic remobilization and resedimentation in distal terrestrial settings in response to large-volume rhyolitic eruptions: examples from the Plio-Pleistocene volcaniclastic sediments, central Japan

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Abstract

Volcaniclastic successions from the Plio-Pleistocene sediments, central Japan, have revealed large-scale volcaniclastic resedimentation under fluvial and lacustrine settings. The Ebisutoge-Fukuda tephra, at the Plio-Pleistocene boundary (~1.75 Ma), records post-eruptive volcaniclastic resedimentation in spatially separated fluvial basins, more than 100 km from the source. The resedimented volcaniclastic material at distal locations originated from unconsolidated deposits of a climactic, large ignimbrite-forming eruption. Temporal and spatial changes to the distal fluvial system were caused by the sudden introduction of large volume of volcaniclastic material following the eruption. Near to the source, a meandering river system was replaced by a braided river system with debris flows and hyperconcentrated flows due to a large volume introduction of volcaniclastic debris, whereas distal areas maintained a meandering river system. Flood-flow deposits decrease with increasing distance from the source. Not only the proximity to the source and temporal change of sediment influx but ignimbrite distribution in the hinterland and topography also control volcaniclastic resedimentation in distal fluvial basins. The Pliocene Mushono volcanic ash layer (~2.3 to 2.4 Ma) shows the distal fluvio-lacustrine deltaic resedimentation of volcaniclastic material. Reworked volcaniclastic deposits show coarsening-upward succession representing delta progradation. In the aftermath of the eruption, a large volume of volcaniclastic debris reworked and discharged into the basin. This resulted in the active fluvial system debouching into a standing body of water, delta formation and delta progradation into the lake. Cobble-sized floating pumice clasts included in prodelta facies and thick reworked deposits imply that the origin of resedimented volcaniclastic material was derived from large-volume ignimbrite near to the source volcano.

In large-scale volcaniclastic resedimentation, most of distal reworked volcaniclastic material is originated from voluminous ignimbrite in proximal source area rather than distal ash-covered landscapes or hillslopes. Concepts of reworking styles suggested for cone type stratovolcanoes by previous researchers are not fully sufficient to explain the distal volcaniclastic resedimentation induced by large-scale rhyolitic eruptions. Ignimbrite nature and distribution relative to topography and drainage pattern are key to the enhancement of large-scale volcaniclastic resedimentation extending to further locations. It is evident that proximity to the source ignimbrite and temporal influx change into the basin are the major controlling factors on the resedimentation styles in distal areas from source volcanoes.

Key-words : distal setting, ignimbrite-forming eruptions, rhyolitic volcanism, terrestrial setting, volcanic hazards, volcaniclastic resedimentation

Introduction

Volcanism can provide an abundant volume of ejecta to a wide area of terrestrial and marine depositional environments. Volcanic products can be transported several hundreds to thousands of kilometers away from the volcanoes by eruptive processes (e.g., pyroclastic fall, surge, and flow; Cas and Wright, 1987). Apart from the primary eruptive processes, others such as various gravity and stream processes exemplified by debris flows, hyperconcentrated flows, dilute fluvial flood flows, and turbidity and storm currents in the aftermath of the eruptions, can cause large-volumes of volcaniclastic debris to be redistributed and resedimented to areas further from the source volcanoes (e.g., Smith, 1987; Scott, 1988; Newhall and Punongbayan, 1996; d'Atri *et al.*, 1999, Kataoka and Nakajo, 2002). The volcaniclastic resedimentation has been well evidenced by modern and ancient deposits around andesitic-dacitic stratovolcanoes with less than 10s of km^3 of volcanic ejecta. Direct observations during last century such as the eruptions of Santa María (Kuenzi *et al.*, 1979), Fuego (Vessell and Davies, 1981), Mount St. Helens (Collins and Dunne, 1986; Scott, 1988), and Mount Pinatubo (Newhall and Punongbayan, 1996) in particular, have provided details of volcaniclastic resedimentation and its impact on surrounding environments around cone-type stratovolcanoes.

Apart from these, volcaniclastic resedimentation induced by large-volume rhyolitic ignimbrite-forming eruptions (with 100s of km^3 of eruptive volume) causes marked impacts on surrounding sedimentary basins. It is expected that harmful high-sediment-laden discharge (e.g. debris flows, hyperconcentrated flows, and flood flows) can occur frequently in a wide area and can modify the topography with large amounts of sediments. At present, such a large-scale resedimentation associated with large-volume ignimbrite-emplacing eruptions has occurred only infrequently and it is therefore difficult to observe directly. Hence, evidences of impact by a large-scale volcaniclastic resedimentation are limited to studies of ancient deposits. Although studies of rhyolitic volcanism-induced resedimentation have been addressed recently (Walton, 1986; Buesch, 1991; Shane, 1991; Nakayama and Yoshikawa, 1997; Kataoka and Nakajo, 2002; Manville, 2002), conceptual discussions on resedimentation are still lacking (Orton, 1995; Kataoka, 2002a).

In contrast to the rather poor understanding of the reworking of volcaniclastic debris after the eruption, primary fallout deposits and ignimbrite by caldera-forming eruptions have been extensively studied (e.g., Sparks and Walker, 1977; Wilson, 1985). Wide area correlation between source ignimbrite and distal co-ignimbrite ash has been enhanced especially in the Tertiary to Quaternary successions (Self and Sparks, 1981; Machida, 1999; Shane, 2000). Silicic widespread tephra can be commonly identified as solitary beds in distal alluvial successions. As a result, the tephra itself shows a time-equivalent-horizon. The resedimentation of widespread tephra, therefore, shows the relationship between individual eruptions and resedimentation of volcaniclastic debris and quick sedimentary response to each eruption in a short time span.

In this paper, in order to consider both fluvial and lacustrine systems of terrestrial settings, two major widespread tephras have been dealt with. The Ebisutoge-Fukuda tephra, the Plio-Pleistocene boundary, indicates large magnitude volcanism and distal fluvial reworking of volcaniclastic material. As the representative of distal fluvio-lacustrine setting, the Pliocene Mushono volcanic ash layer has been focused. Also this paper concerns the conceptual discussion on distal volcaniclastic resedimentation in response to voluminous rhyolitic eruption, comparing with the other representative Plio-Pleistocene tephras.

The purpose of this paper is to understand (1) a large-scale volcaniclastic resedimentation induced by a rhyolitic eruption; (2) volcanic influence on surrounding basin including sedimentary response to the eruption; and (3) the essential factors controlling the volcaniclastic resedimentation in distal locations from the source volcanoes.

Example of distal fluvial volcaniclastic resedimentation: Ebisutoge-Fukuda tephra

Geological Background

The Ebisutoge-Fukuda tephra (Nagahashi *et al.*, 2000: 1.75 Ma), central Japan, records complex volcanism and resedimentation styles of volcaniclastic deposits in the surrounding multiple distal fluvial and marine basins (Kataoka *et al.*, 2001; Kataoka and

Nakajo, 2000, 2002). This tephra covered over 290,000 km^2 of Honshu Island and its surroundings, extending for more than 300 km from the probable source situated near Mount Hotakadake (Fig. 1) in the Japan Northern Alps, central Japan (Harayama, 1992; Nagahashi *et al.*, 2000). The total amount of ejecta is more than 380 to 490 km^3 (Kataoka *et al.*, 2001). According to Kataoka *et al.* (2001), primary volcaniclastic deposits of the Ebisutoge-Fukuda tephra resulted from five eruptive phases with phreatoplinian, plinian, and ignimbrite eruptions. The biggest ignimbrite forming eruption in the final phase resulted in a large amount of ejecta, equivalent to more than a two-thirds of total bulk volume of the Ebisutoge-Fukuda eruption volcanic products. A very large volume of non-welded and unconsolidated volcaniclastic material produced by the eruption of Ebisutoge-Fukuda tephra was easily eroded and remobilized. This means that the main resedimentation initiated soon after the final ignimbrite forming stage.

Characteristics of deposits

The Ebisutoge-Fukuda tephra in distal fluvial basins comprises pyroclastic fall deposits and thick resedimented volcaniclastic deposits (Figs. 2, 3). The succession is well exposed in the Tokai, Kobiwako, Osaka, Shobudani, and Uonuma sedimentary basins (Fig. 1). The fall deposits consist of several fall units and comprise well-sorted fine- to medium-grained vitric to vitrocrystal ash particles. The deposits are characterized by mantle bedding, normal and inverse graded bed, absence of trough cross-stratification and ripple cross-lamination. On the other hand, resedimented vol-

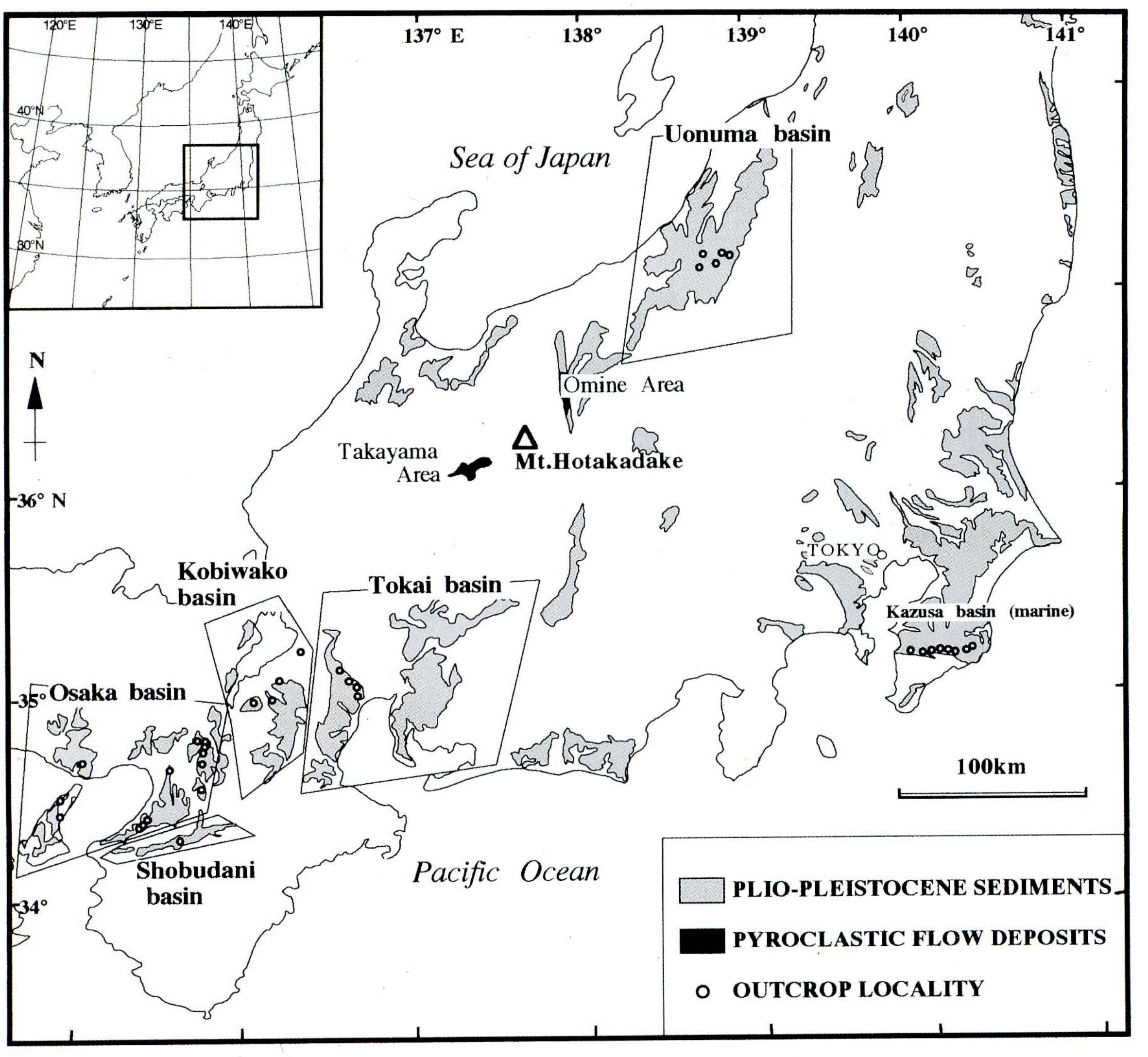

Fig. 1 Distribution of the Plio-Pleistocene sediments and localities where the Ebisutoge-Fukuda tephra are exposed. This tephra reached over 300 km far from eruption center, Mount Hotakadake (open triangle).

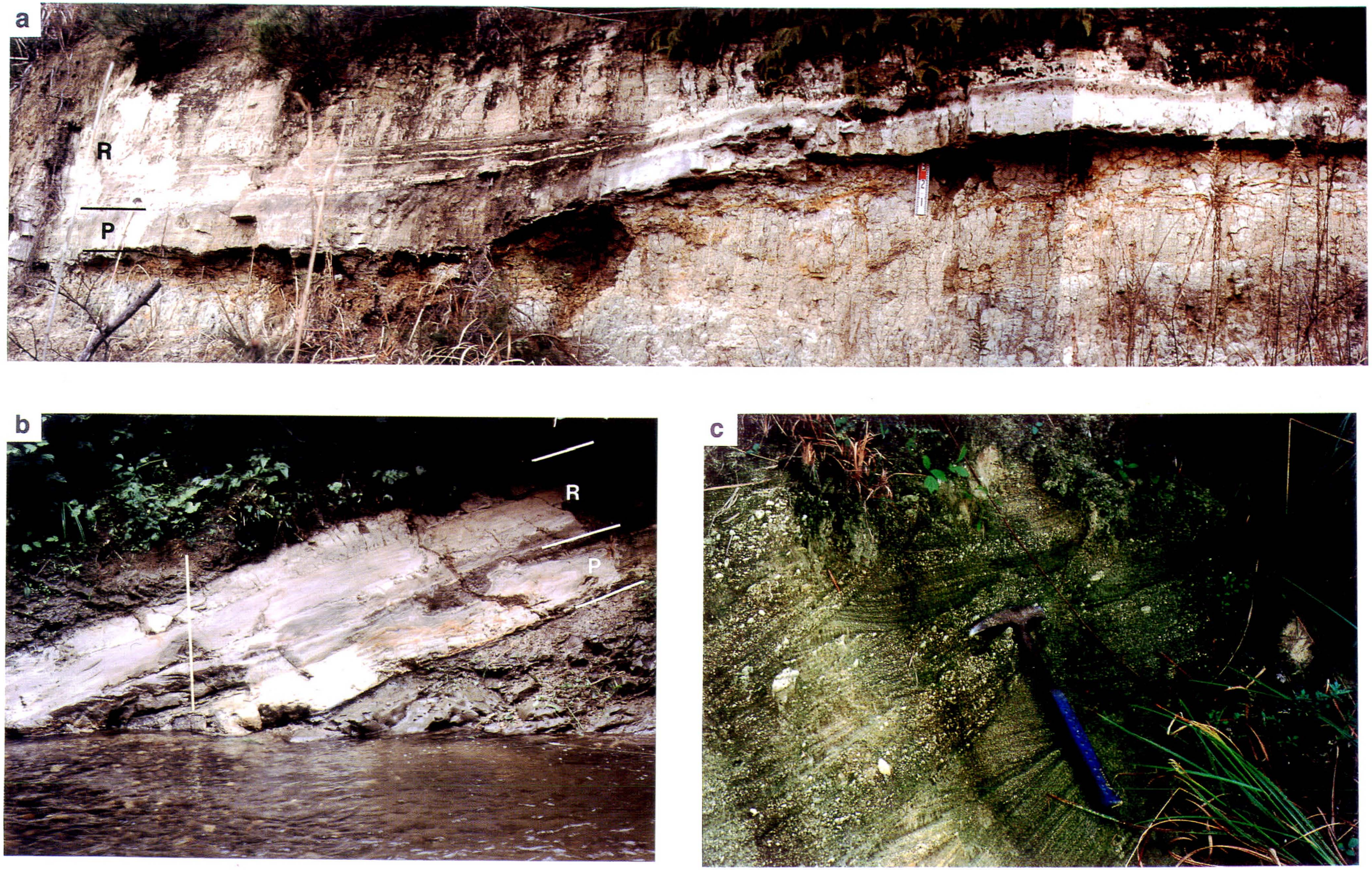

Fig. 2 Outcrops of the distal Ebisutoge-Fukuda tephra. a) Primary pyroclastic fall deposits (P) show mantle bedding along the previous topography (Kobiwako basin). On the other hand, reworked volcaniclastic deposits (R) onlap the fall deposits and are horizontally stratified. Ruler is 30 cm long. b) Thick primary pyroclastic-fall deposits (~ 50 cm thick: P) are overlain by thin resedimented volcaniclastic deposits (< 60 cm thick: R) in the Uonuma basin. c) Trough cross-stratifications consist of glass shards and rounded pumice clasts (Tokai basin). This indicates reworking of volcaniclastic material by fluvial processes.

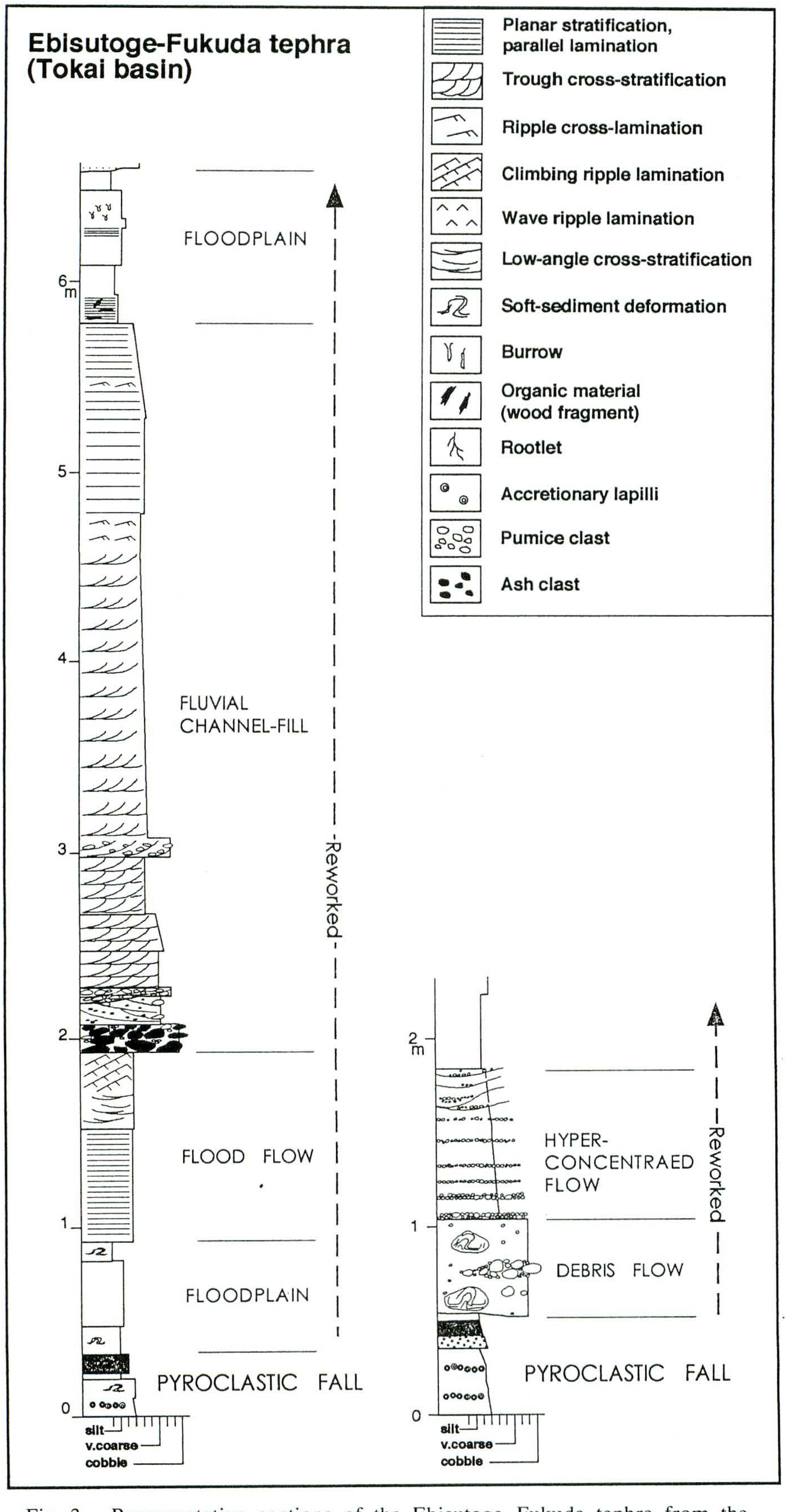

Fig. 3 Representative sections of the Ebisutoge-Fukuda tephra from the Tokai basin. These are most proximal exposures in west of the volcanic source. The sections show debris-flow, hyperconcentrated flow and channel fill deposits as dominant facies.

caniclastic deposits comprise vitric ash, pumice clasts, ash clasts, and epiclastic debris. They have a wide range in grain-size ranging from clay size (vitric particle) to cobble size (pumice clasts). The reworked deposits display sedimentary structures including trough cross-stratification, horizontal stratification, ripple cross-lamination, parallel thin lamination all of which indicate fluvial processes. Distally reworked volcaniclastic deposits of the Ebisutoge-Fukuda tephra can be subdivided into five sedimentary facies. These are interpreted as debris flow deposits, hyperconcentrated flow deposits, channel-fill deposits, flood deposits, and floodplain deposits with minor amounts of flood deposits (Kataoka and Nakajo, 2002).

Resedimentation style

The Tokai basin is the most proximally conditioned among the western basins, and is ~160 km south-southwest from the source. Thickness of the resedimented part is up to 10 m. The succession is characterized by multistoried channel fill deposits with occurrence of debris flow and hyperconcentrated flow facies. This indicates that volcaniclastic resedimentation occurred in a braided system with a high discharge debris and hyperconcentrated flow in the aftermath of the eruption. The top of reworked volcaniclastic sediments is commonly occupied by floodplain facies implying recovering stable channels at the end of the reworking processes (Fig. 3).

The Kobiwako basin and Osaka basin lie at 170 to 200 km and 240 to 320 km southwest from the source, respectively. Floodplain facies is predominant in both basins indicating that resedimentation occurred in a meandering river system.

In the Shobudani basin (~290 km southwest from the source), south of the Osaka basin, the succession consists of only primary pyroclastic-fall deposits. In spite of being close to the Osaka basin, the Shobudani fluvial system was probably separated from the Osaka basin due to surrounding higher mountain ranges (Oka, 1978; Kataoka and Nakajo, 2002) so that major volcaniclastic resedimentation could not generate.

The Uonuma basin, most proximal area, is approximately 140 km northeast from the source. Distal pyroclastic fall deposits are thick and multiple fall units are well preserved. In contrast to thick pyroclastic fallout, reworked sediments are less in thickness (Figs. 2, 7). A meandering river system developed in the aftermath of the eruption in spite of proximity to the source due to a less influx of ignimbrite upstream of the basin (Nagahashi, 1998; Kataoka and Nakajo, 2002).

Example of distal fluvio-lacustrine volcaniclastic resedimentation: Mushono volcanic ash

Geological background

The Mushono volcanic ash layer (~2.3 to 2.4 Ma: Takaya, 1963; Satoguchi *et al.*, 1999) is one of the widespread Pliocene tephras in central Japan. The correlatives of the volcanic ash layer are recognized in other separate sedimentary basins (Fig. 4), including the Tokai basin (Koyashiro volcanic ash: Miyamura *et al.*, 1981) and the Kakegawa basin (Shiraiwa volcanic ash: Mizuno *et al.*, 1987). Intra- and interbasinal correlation of these volcanic ashes have been carried out by Yoshikawa and Yoshida (1989), Yoshikawa *et al.* (1991), Satoguchi *et al.* (1996) and Satoguchi *et al.* (1999) by integrating of chronostratigraphy, petrography and age determinations.

Although the eruptive center of the Mushono volcanic ash layer has not been clarified in previous studies, two eruptive candidates can be proposed here. Satoguchi (1997) suggested that the possible eruptive source was situated in the Chubu Area, central Japan (Fig. 4) on the basis of distribution patterns, lithofacies, and petrographic features of widespread Plio-Pleistocene tephras concerned with migration of the active volcanic areas. Another candidate is situated around Mt. Oginosen in the San'in Area, southwestern Japan, where voluminous Utaosa rhyolitic tuffs of the Teragi Group are distributed (Furuyama, 1989) and their ages are close to that of the Mushono-Koyashiro-Shiraiwa volcanic ash layers (Uto *et al.*, 1994; Furuyama *et al.*, 1998). Both probable source areas are more than 150 to 200 km away from the study area of the Kobiwako basin.

Characteristics of deposits

On the basis of the transport style, the distal facies of the Mushono volcanic ash layer in the study area is subdivided into two: primary pyroclastic-fall deposits and reworked volcaniclastic deposits (Figs., 5, 6). Primary fall deposits are composed of well-sorted, fine- to medium-grained glass shards, free crystals, and micro-pumice particles (Kataoka, 2002a). Reworked volcaniclastic deposits, consisting of vitric ash, pumice clasts, free crystals, and epiclastic debris, show a wide range in grain-size, i.e., from clay size (vitric particle) to cobble size (pumice). The resedimented volcaniclastic deposits show a coarsening-upward succession representing fluvio-lacustrine deltaic progradation (Fig. 6). The deltaic progradational succession consists of seven sedimentary facies, which are pyroclastic fallout,

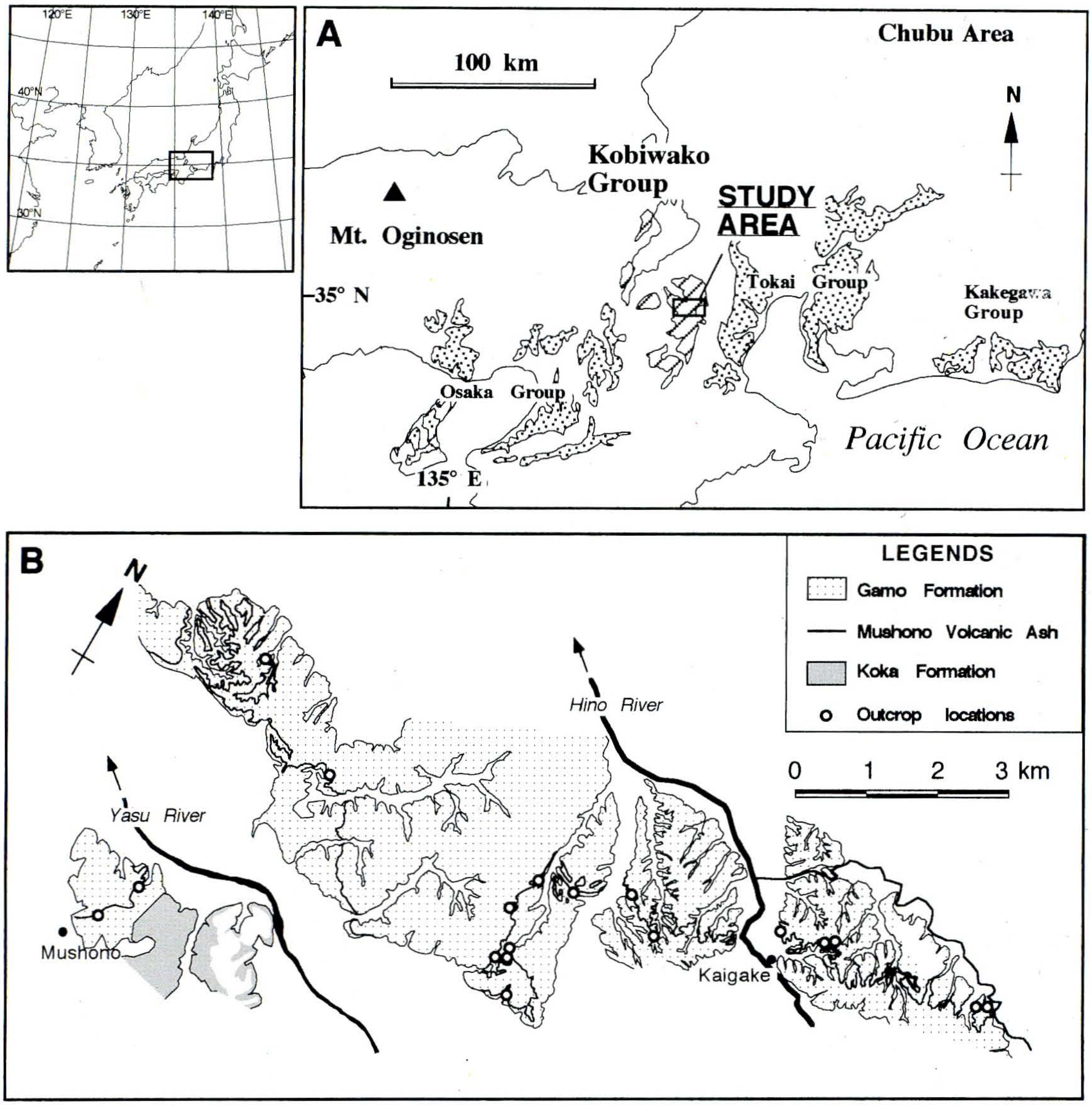

Fig. 4 a) Distribution of the Plio-Pleistocene sediments in Kinki district. The Mushono volcanic ash layer is distributed in the Kobiwako basin. Although eruption center for this ash is still unclear, there was certain coeval volcanic activities in the San'in area, where Mt. Oginosen is situated, and also in the Chubu area. b) Geologic map and distribution of the Mushono volcanic ash layer in the Kobiwako basin. Geologic map based on Kaigake Research Group (1972), Kobiwako Research Group (1977), Kawabe (1989), Yoshikawa and Yamasaki (1998).

prodelta, mouth bar, distributary channel, hyperconcentrated flow, interdistributary lowland or floodplain, and slump deposits (Kataoka, 2002a, b).

Resedimentation style

Vertical facies change of volcaniclastic succession reveals the sedimentary response to a large-volume rhyolitic eruption (Fig. 6). In the aftermath of the eruption of the Mushono volcanic ash, a large volume of volcaniclastic debris including gravel-sized pumice loads was discharged into the fluvial system. Multistoried distributary channel deposits indicate active fluvial tracts due to sudden large-volume influx of unconsolidated volcaniclastic material into terrestrial surroundings. The fluvial system directly debouched into the lake resulting in the delta formation and progradation. Cobble-sized floating pumice clast included in prodeltaic facies and thick reworked deposits imply that the origin of resedimented volcaniclastic material was probably derived from large-volume ignimbrite near the volcano. On the other hand, the dominant occurrence of interdistributary or floodplain facies near the top of

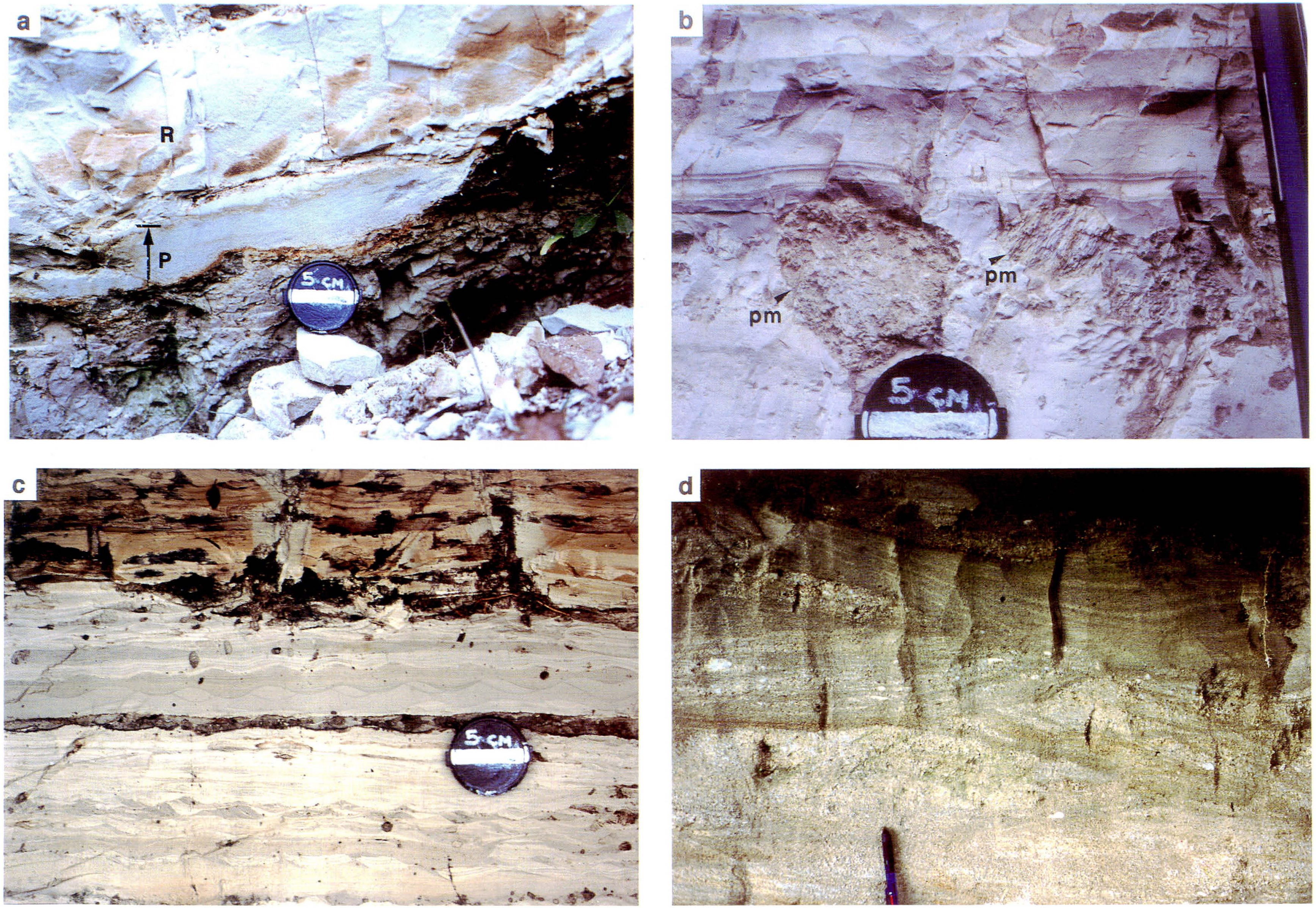

Fig. 5 Field photographs of the Mushono volcanic ash layer. a) Primary pyroclastic-fall deposits (**P**), directly overlie non-volcanic gray colored silt bed, are overlain by resedimented volcaniclastic deposits (**R**). The fall deposits are normally graded. b) Round isolated pumice clasts (floating pumice: **pm**) are included in laminated silt-sized ash matrix (prodelta facies). c) Wave ripple lamination of the mouth-bar facies. d) Trough cross-stratification comprises granule- to pebble-sized pumice and fine-grained vitric ash (distributary channels).

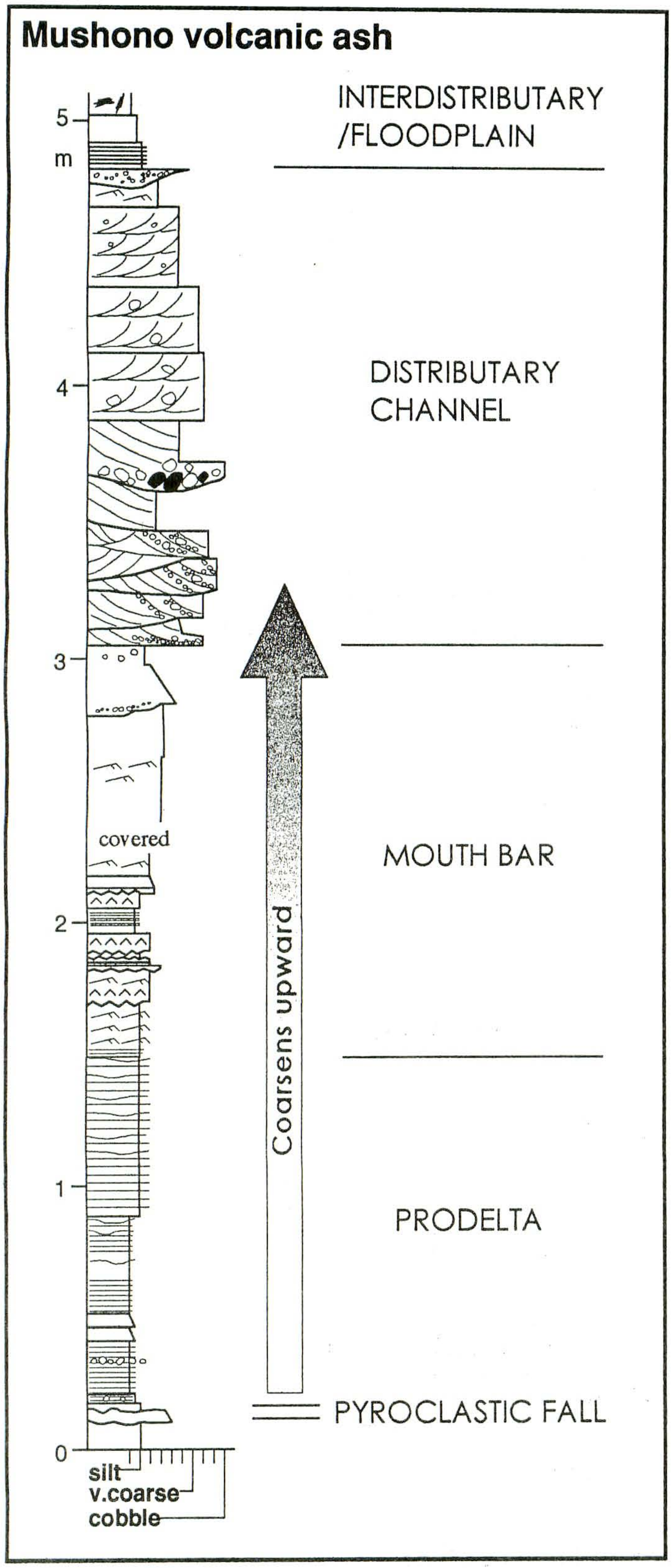

Fig. 6 The facies interpretations of the Mushono volcanic ash layer showing a lacustrine deltaic sedimentation. Generally facies superposition changes upward from primary fall deposits, through prodelta, mouth bar, distributary channel, into interdistributary or floodplain. Legend as in Fig.

the reworked Mushono volcanic ash indicates the development of an inactive fluvial system such as a stagnant alluvial to delta plain at the end of the reworking processes. This system change was concordant with the diminished influx of volcaniclastic debris into the basin at the end of reworking phase.

Origin of resedimented volcaniclastic material in distal terrestrial settings

The origin of resedimented volcaniclastic material in multiple distal fluvio-lacustrine basins will attest the triggering factors of resedimentation. It should be clear that reworked material is from proximal volcaniclastic debris or from surrounding hinterland and/or hillslopes in distal areas.

The distal fall deposits of the Ebisutoge-Fukuda tephra and the Mushono volcanic ash are all composed of ash-size particles and lack pebble-cobble sized pumice clasts. On the other hand, the overlying reworked volcaniclastic deposits contain decimeter-sized pumice clasts. Pebble- to cobble-sized large pumice clasts are often recognized in plinian deposits and ignimbrite (Cas and Wright, 1987). However, transportation distance of decimeter-sized pumice clasts by plinian eruption is limited to 50 to 60 km from the source due to their aerodynamic property (Walker, 1980). The study area is situated probably more than 150 km from the eruption center, so that the pumice must be eroded from proximal to volcano and not from ash-covered landscapes in distal areas.

On the basis of ash distribution, the lake of the Mushono volcanic ash layer had probably less catchment area than the present Lake Biwa which has approximately 3,200 km^2 of the area (Shiga Prefectural Government, 2002). Distal fall deposits of the Mushono volcanic ash are usually 2 to 5 cm thick in the Kobiwako basin. If the ash-covered areas assumed less than 3,200 km^2 with 5-cm-thick ash fallout, it totals 0.16 km^3 of volume. Therefore, in the Mushono volcanic ash, at most 0.16 km^3 of tephra volume could be removed and there is only a little possibility for them to be preserved in strata. Hence it would be difficult for meter-thick reworked successions to form. To compensate the reworked volume of the Mushono volcanic ash (more than 5 m of reworked thickness), another influx of volcaniclastic debris was necessary. The additional debris was probably delivered from the extra-basin, i.e., proximal area to the volcano. Generally, the Japanese widespread tephras, which are traceable for more than 100 km across, have a large-volume (10s km^3 to 100s km^3)

of volcaniclastic material (Kamata *et al.*, 1997; Machida, 1999; Kataoka *et al.*, 2001). Mostly these widespread tephras were related to large-volume ignimbrite emplacing eruptions. Probably the eruption of the Mushono volcanic ash had large-volume ignimbrite eruption due to wide dispersal and thick resedimented volcaniclastic deposits in distal basins. Compared to 10s km^3 to 100s km^3 of ignimbrite volume upstream of the drainage basin, the estimated volume of ash covered plain and hillslope (less than 0.16 km^3) in distal areas is negligible.

Figure 7 shows the relationship between the thickness of fall deposits and that of resedimented volcaniclastic deposits. These examples are from the Ebisutoge-Fukuda tephra, Mushono volcanic ash, Pliocene Ohta tephra (Nakayama and Yoshikawa, 1997), Pliocene Souri tephra (Nakayama *et al.*, 1996), and Pliocene Bando 1 volcanic ash (Nakamae and Nakayama, 1998) in distal fluvial and fluvio-lacustrine settings in central Japan. All these have common characteristics of simple organization of the tephra sequence representing centimeter- to decimeter-thick pyroclastic fall deposits overlain by meter-thick reworked volcaniclastic deposits in distal terrestrial settings (Fig. 7). Comparison of these tephras does not show a major positive relationship between pyroclastic fall deposits and reworked deposits in thickness. This may be contrary to intuitional prediction of positive relationship between fall thickness and reworked one (i.e., the more fallout deposition, the more reworking occurs). This shows that the main resedimented material is not derived from fall deposits in the hinterland or surrounding hillslopes. Therefore, the existence of other large volumes of volcaniclastic influx (reworking of ignimbrite) is necessary to make such a thick resedimented succession.

Generally, ignimbrite containing abundant fine ash particles shows lower permeability than coarse-grained and open-worked pumiceous plinian deposits (Collins and Dunne, 1986; Cas and Wright, 1987). The low permeability leads to intensive erosion of sediments that subsequently increase the remobilization of volcaniclastic material (White *et al.*, 1997). Moreover, destruction of sediment-stabilizing vegetation would be prominent in proximal areas rather than in areas distant from the volcano (e.g., Orton, 1996). In the proximal area, especially unconsolidated loosely packed ignimbrite has a

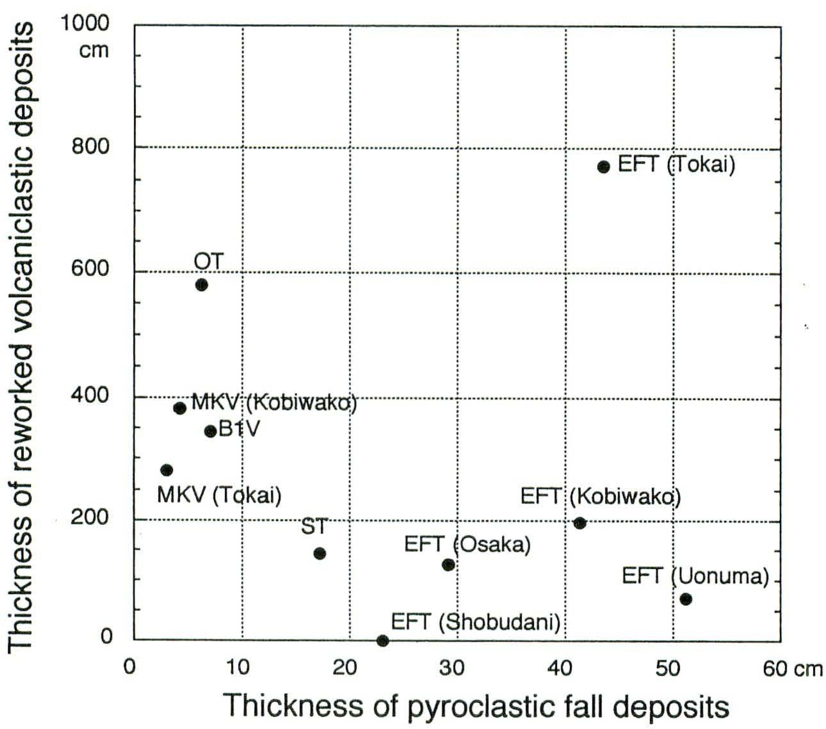

Fig. 7 Thickness ratio of pyroclastic fall deposits to reworked volcaniclastic deposits. Examples are from Japanese Plio-Pleistocene tephras. EFT: Ebisutoge-Fukuda tephra, MKV: Mushono-Koyashiro volcanic ash, OT: Ohta tephra (Nakayama and Yoshikawa, 1997), ST: Souri tephra (Nakayama et al., 1996), B1V: Bando 1 volcanic ash (Nakamae and Nakayama, 1998).

higher reworking potential than the fallout deposits on an alluvial plain.

Thus, major reworked volcaniclastic material was from large-volume volcanic ejecta in the proximal area from the source volcano. The presence of non-welded ignimbrite in the proximal area is a key to the generation of the volcaniclastic resedimentation in distal fluvial and fluvio-lacustrine setting in the aftermath of rhyolitic eruptions (Table 1).

Facies models for resedimented volcaniclastic deposits in distal terrestrial settings

Spatial facies variations

Proximal-distal facies changes of the resedimented volcaniclastic deposits have been documented by previous research workers (the Volcano Fuego, Guatemala, late Pleistocene to present: Vessell and Davies, 1981; the Deschutes Formation, Oregon, Neogene: Smith, 1987; the Ellensburg Formation, Washington, late Miocene: Smith, 1988). These examples are mainly related to eruption of stratovolcanoes with probably less than 1 to 10s km^3 of bulk volume. The example of the Ebisutoge-Fukuda tephra shows the proximal-distal facies change in three westerly situated basins including Tokai, Kobiwako and Osaka basins associated with > 100s km^3 of volume of the rhyolitic eruption (Fig. 8). Debris-flow and hyperconcentrated-flow deposits are present only in the Tokai basin. The Tokai basin was characterized by a braided river system whereas the

Table 1 Characteristics related to reworking potential for plinian and ignimbrite eruptions.

Eruptive style	Composition	Volume of products	Grain size, sorting of proximal deposits	Permeability of deposit	Devegetation	Potential for reworking
Plinian eruption	Generally andesitic to rhyolitic	1 to 10s of km^3	Coarse pumice, well sort	High	Moderate in proximal area	Low
Igimbrite eruption	Generally dacitic to rhyolitic	10s to 100s of km^3	Coarse pumice with fine matrix, poor sort	Low	High in proximal area	Very high

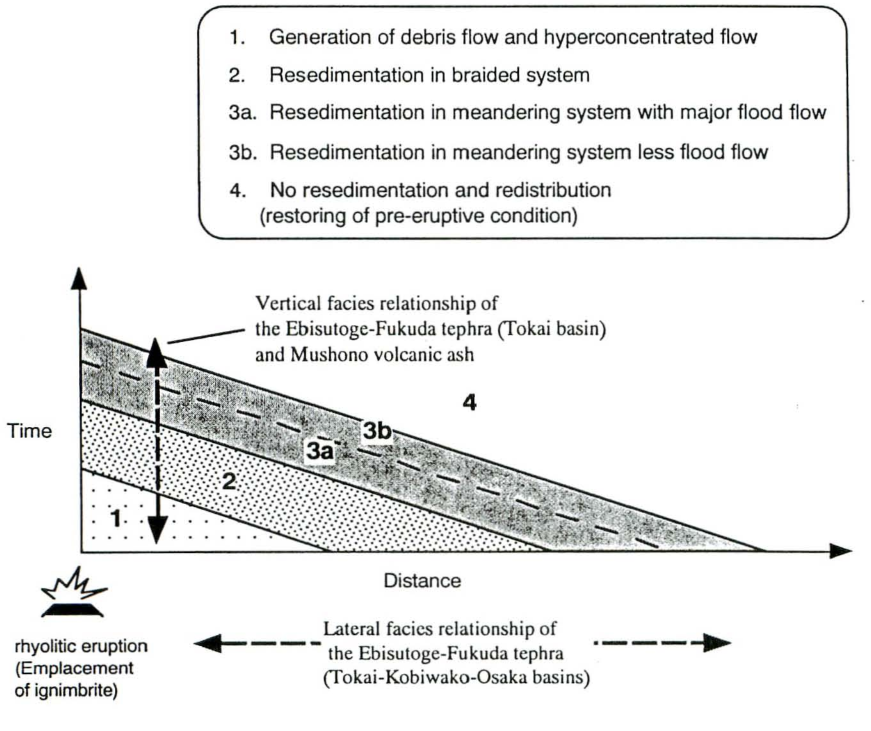

Fig. 8 Variations of volcaniclastic resedimentation in the aftermath of the major eruptions. Distance and time duration directly or indirectly related with sediment influx change into the basin. This results in different resedimentation styles.

Kobiwako and Osaka basins contained a meandering river system. The Kobiwako-Osaka basinal comparison shows a decrease in flood-flow deposits with increasing distance from the source. Thus, the Tokai-Kobiwako-Osaka basinal facies changes rely systematically upon decrease in supplied volume of volcaniclastic material with distance from the source (Fig. 8). There seems to be a common trend in the relationship between resedimentation style and volume of debris introduced to the basin (i.e., distance from the source) in small- to large-scale volcaniclastic resedimentation. But for large-scale ones (i.e., rhyolitic eruption induced), the distance from the ignimbrite bodies is represented better than that from the eruptive source (i.e., vent).

In large-scale volcaniclastic resedimentation, with 10s to 100s km^3 of volume eruption, not only the proximity to the source but other factors also play an important role, especially in places far from the source volcanoes. The topography of the volcanic region controls the augmentation of redistribution of volcaniclastic material. The Pleistocene Mangatarata Formation in New Zealand contains numerous thick reworked silicic tuffs intercalated with fluvial and lacustrine sediments (Shane, 1991). These reworked tuffs deposited in areas 100 to 200 km from the volcanic source of the Taupo Volcanic Zone (TVZ) which has large caldera morphology (Wilson *et al.*, 1984). Even though the ignimbrite forming eruption occurred in 0.5 Ma (Wilson *et al.*, 1984) with more than 300 km^3 of rock volume proximal to the volcano, no correlative resedimented volcaniclastic deposits in distal fluvial facies of the Mangatarata Formation could be found. Shane (1991) concluded that the Main Axial Ranges situated in the east of TVZ became a barrier for volcaniclastic transport eastward. Thus considering distal reworking, topographical obstructions lying between eruptive source and basin, limit the influx of the sediment from ignimbrite, and subsequently control the reworking of volcaniclastic debris.

The case of the eruption of Ebisutoge-Fukuda tephra, north-south trending range in the east of the eruptive center prevented the ignimbrite deposition to the east. This resulted in the relatively small introduction of resedimented volcaniclastic material into the Uonuma basin even though the place was near to the source. The Osaka and Shobudani basins lie at almost the same distance and direction from the source, but the latter was isolated by a mountain range so that it received only primary pyroclastic-fall deposits. These examples show that the facies variation of the resedimented volcaniclastic deposits implies distribution pattern of pyroclastic flow deposits, topography, drainage patterns, and interrelationship between separated distal basins.

Temporal (vertical) facies changes

Vertical facies changes in the Ebisutoge-Fukuda tephra indicate that depositional environments changed drastically after the eruption. Changes to the river system were caused by the sudden introduction of large volumes of volcaniclastic material following the eruption. In the Tokai basin, a meandering river system that had developed before the eruption was replaced by a braided river system with sediments deposited from debris flows and hyperconcentrated flows. This braided river system reestablished to the meandering river when there was a lessening of the volcaniclastic influx into the basin. These facies changes are concordant with the concept of syn-eruption sedimentation and inter-eruption sedimentation around stratovolcanoes (e.g., Vessell and Davies, 1981; Smith, 1991; McPhie *et al.*, 1993).

The vertical facies changes of the Mushono volcanic ash show the lacustrine-deltaic resedimentation of volcaniclastic debris after the major eruption. The active fluvial system and the delta progradation into the lake were controlled by the influx of a large-volume of volcaniclastic debris after the eruption. Such a progradation of delta in a volcanic setting is conspicuously developed when large volumes of volcaniclastic material were introduced into the standing body of water (Kuenzi *et al.*, 1979; Manville, 2001). The resedimented volcaniclastic facies near the top of the Mushono volcanic ash layer indicates that the stagnant environment in terrestrial surroundings was due to the diminished influx of volcaniclastic debris.

In the concepts of Vessell and Davies (1981), Smith (1991) and others, the beginning of the reworking phase will be characterized by a high-sediment-load delivery into the basin. Accordingly, it is expected that subaqueous facies (the lowermost part) of the reworked Mushono volcanic ash layer may contain debris flow deposits or turbidites implying high-energy conditioned sediment delivery. However, the depositional sequence shows low-energy environmental sedimentation (prodelta sedimentation) at the bottom and sedimentation from active fluvial system with high-discharge hyperconcentrated flow in the upper part. This occurrence is presumably due to ignimbrite origin of resedimented material. There was a delay in the spread of volcaniclastic resedimentation from ignimbrite to downstream of the basin. If major resedimented volcaniclastic debris derived from fallout material covered the surrounding areas, the succession should be seen, as suggested by Vessell and Davies (1981) and others.

A lake can act as a reservoir to accumulate voluminous resedimented material. If there was a lacustrine system for the Mushono volcanic ash layer on an alluvial plain, the resedimentation of volcaniclastic debris would be delayed further downstream of the fluvial system. The sediment impoundment upstream also causes a delayed response to the amount of volcanic supply (e.g., Manville, 2001; Segschneider *et al.*, 2002) resulting in finer-grained resedimented facies in the lower sequences.

Thus the sedimentary response to the eruption at the distal locus corresponds with changes in sediment yield of volcaniclastic material that increases suddenly after the eruption and decreases as time passes, although sometimes the water and sediment impoundment interrupts the yield in the aftermath of the rhyolitic eruptions.

Implications for volcanic hazards with large-volume rhyolitic eruptions

Duration of resedimentation after major eruptions

From a viewpoint of volcanic hazards, duration of volcaniclastic resedimentation after eruptions has been gathering much attention. When an eruption is from small to medium scale of scoria cones or stratovolcanoes (up to 10s km^3 of volume), resedimentation of volcanic ejecta will probably terminate within 10s of years (e.g. Vessell and Davies, 1981; Orton, 1996). When a rhyolitic ignimbrite emplacing eruption emanates a large volume of volcanic products (10s to 100s km^3 of volume), it is expected that resedimentation will persist much longer so that we may not directly observe or predict the termination of the resedimentation.

Previous work on the large-scale fluvio-lacustrine resedimented tephras in the Pliocene Tokai Group showed the duration of volcaniclastic reworking (Ohta tephra: Nakayama and Yoshikawa, 1997; Bando 1 volcanic ash: Nakamae and Nakayama, 1998). They concluded that fluvial reworking would persist with at least 1000s to 10000s of years duration on the basis of the concept of bounding hierarchy of fluvial sediments by Miall (1991).

A number of volcanic ash layers (more than 10s to 100 of intercalations) in the Plio-Pleistocene succession of Honshu Island, central Japan indicates a high frequency of volcanic eruptions including small- to large-scale ones (e.g. Yoshikawa, 1976; Machida and Arai, 1992; Machida, 1999; Satoguchi *et al.*, 1999). Nagahashi *et al.* (2001) discussed the frequency of large-scale pyroclastic flow eruptions during late Miocene to Pleistocene in Honshu and Kyushu islands. Large-volume pyroclastic forming eruptions (> 10s km^3) occurred at intervals of 2000 to 5000 years in these islands. Including small-scale ones, volcanoes erupted, probably, at least every 1000 years during Plio-Pleistocene. Therefore, if the duration of volcaniclastic resedimentation were 1000s to 10000s of years as suggested by Nakayama and Yoshikawa (1997), there may be intercalation of newly fallout tephra within previous reworked volcaniclastic successions. However, such an occurrence in distal resedimented volcaniclastic deposits cannot be observed in this study and has not been reported previously. Fundamentally, Miall's concept of the bounding hierarchy should not be applied to volcaniclastic sedimentation due to much difference in supplied volume of sediment and occurrence of sedimentary facies (e.g., debris and hyperconcentrated flow facies within distal alluvial succession). Thus, the deduced duration by Nakayama and Yoshikawa (1997) seems to have been overestimated.

Pumice is a major component of volcanic ejecta by rhyolitic explosive eruptions. It is commonly contained in plinian fall deposits and ignimbrite. Pumice clasts with low density are able to float on water for a long time and finally they sink due to water logging. There is a positive relationship between volume (i.e. clast size) of pumice and the sinking time (Whitham and Sparks, 1986; Manville *et al.*, 1998; White *et al.*, 2001). Therefore, the presence of pumice clasts included in reworked volcaniclastic facies may indicate the duration of reworking processes. According to Whitham and Sparks (1986) and White *et al.* (2001), it takes 10s of years for saturation of pebble-sized pumice clast to sink and 100s of years for cobble-sized ones. Although the sinking time of pumice is dependent on the porosity of each pumice, the time can be useful as an approximation. Cobble-sized floating pumice contained in prodelta facies (indicating offshore of lake) of the Mushono volcanic ash layer, therefore, implies that the reworking duration was 10s to 100s of years. Further, no major hiatus or intercalation of siliciclastic succession within resedimented Mushono volcanic ash layer suggests that volcaniclastic resedimentation progressed quickly. Otherwise, we cannot distinguish it as a solitary tephra unit in the non-volcaniclastic succession. Conclusively, such a large-scale volcaniclastic resedimentation related to rhyolitic large-volume eruptions will persist during 10s to 100s of years or to 1000s of years at most.

Implications for ancient volcanism

The Japanese Plio-Pleistocene sediments such as the Osaka, Kobiwako, Tokai, Kakegawa, Uonuma, Kazusa Groups and so on are situated in distal areas from the source volcano. These groups contain more than 10s to 100 of intercalations of volcanic ash layers (e.g., Satoguchi *et al.*, 1999). Most of the volcanic ash beds, which are older than early Pleistocene, have not been correlated to their source volcanoes. Details of volcanism such as eruptive source location, magnitude, style, and history in Pliocene to early Pleistocene time are still vague, because, volcanic products proximal to the source have been easily degraded by tectonic uplifting of the areas. However, distal reworked volcaniclastic deposits directly or indirectly reflect the primary volcanic processes, which may reveal the eruptive style, history, and magnitude. It is meaningful when distal tephras lack the reworked volcaniclastic deposits. This may be indicative of eruptive style, palaeotopography or palaeodrainage at the depositional time. Also understanding of resedimented volcaniclastic facies will contribute to the correlation of tephras that commonly shows lithofacies variation and which create confusion in chronostratigraphy. Thus a sedimentological approach to resedimented volcaniclastic deposits can contribute in unravelling ancient volcanism as well as understanding modern and future perspectives of volcanism-induced sedimentation.

Volcanic hazards with large-volume eruptions

There is a large number of tephras with reworked volcaniclastic deposits in the world. As discussed here, reworked volcaniclastic sequence in distal terrestrial succession implies the presence of a large volume of pyroclastic flow deposits (i.e., ignimbrite) in the hinterland of source areas. Also this indicates a higher frequency of large-scale ignimbrite forming eruptions than previously reported eruptions inferred from the volcaniclastic sequences in the proximal region to the source volcanoes. Researchers tend to estimate the eruptive style and scale of distal tephras only from the primary fall deposits. However, it sometimes leads to errors concerning the eruptive style and also underestimates the scale of these hazardous eruptions. The cases of the Ebisutoge-Fukuda tephra, Mushono volcanic ash layer, and other rhyolitic volcanic ashes documented here show strong contrast as far as pyroclastic fall deposition and reworking deposition are concerned. From the point of view of reworking potential, it is likely that there was no resedimentation even with thick fall deposition at the locus. Vice versa, even though there are no fallout deposits, there is a high possibility for the occurrence of catastrophic resedimentation in the distal places from the eruptive source, once ignimbrite entered into upstream part of the basin (Figs. 7, 9).

Terrestrial debris flows and their deposits are commonly observed on alluvial and volcanic fans. Generally, on an alluvial fan, debris flows are short-lived and rarely extend more than 10 km away from the source (Smith, 1988). Debris-flow and hyperconcentrated-flow deposits, which usually cannot be observed within non-volcanic distal alluvial-plain facies, are often intercalated with volcaniclastic successions in distal alluvial settings. Volcanic debris flows can be generated by the collapse of volcanic edifices or the remobilization of pyroclastic-flow deposits by abundant water from rainfall or snow melting (Major and Newhall, 1989; Manville *et al.*, 2000). The resulting flow can be loaded with abundant volcanic material and can travel more than 100 km from the source (e.g., Mothes *et al.*, 1998; Vallance and Scott, 1997). This indicates that potential hazards of large-scale volcaniclastic resedimentation spread wide tracts away from the source volcanoes. Another factor contributing to wide distribution (reaching farther from the source) of debris flow and hyperconcentrated flow facies in distal setting is the long travel distance of the original source ignimbrite (> 100 km, for eruptions of large ones). Examples from the Ebisutoge-Fukuda tephra and Mushono volcanic ash show that such hazardous flows can travel to distal alluvial plains from the volcanic source if induced by large-volume explosive eruptions.

There are many studies dealing with volcanic hazards and their prevention and mitigation, and which are mostly related to the proximal area to active cone-type stratovolcanoes (e.g., Latter, 1988; McCoy and Heiken, 2000). Although people in the area away from the volcanoes tend to ignore the volcanic hazard, ancient volcaniclastic successions such as the Ebisutoge-Fukuda tephra and the Mushono volcanic ash layer represent the potential risk even far away from the volcano. There is still less understanding of resedimented volcaniclastic sequence, even though resedimentation is one of the most widespread phenomena and which persists for a long time as compared to other primary eruptive processes. Rhyolitic caldera volcanoes, especially implying high potential of large-scale resedimentation, exist in many countries around the world. From the viewpoint of volcanic hazards also, reworked volcaniclastic deposits in terrestrial succession should not be

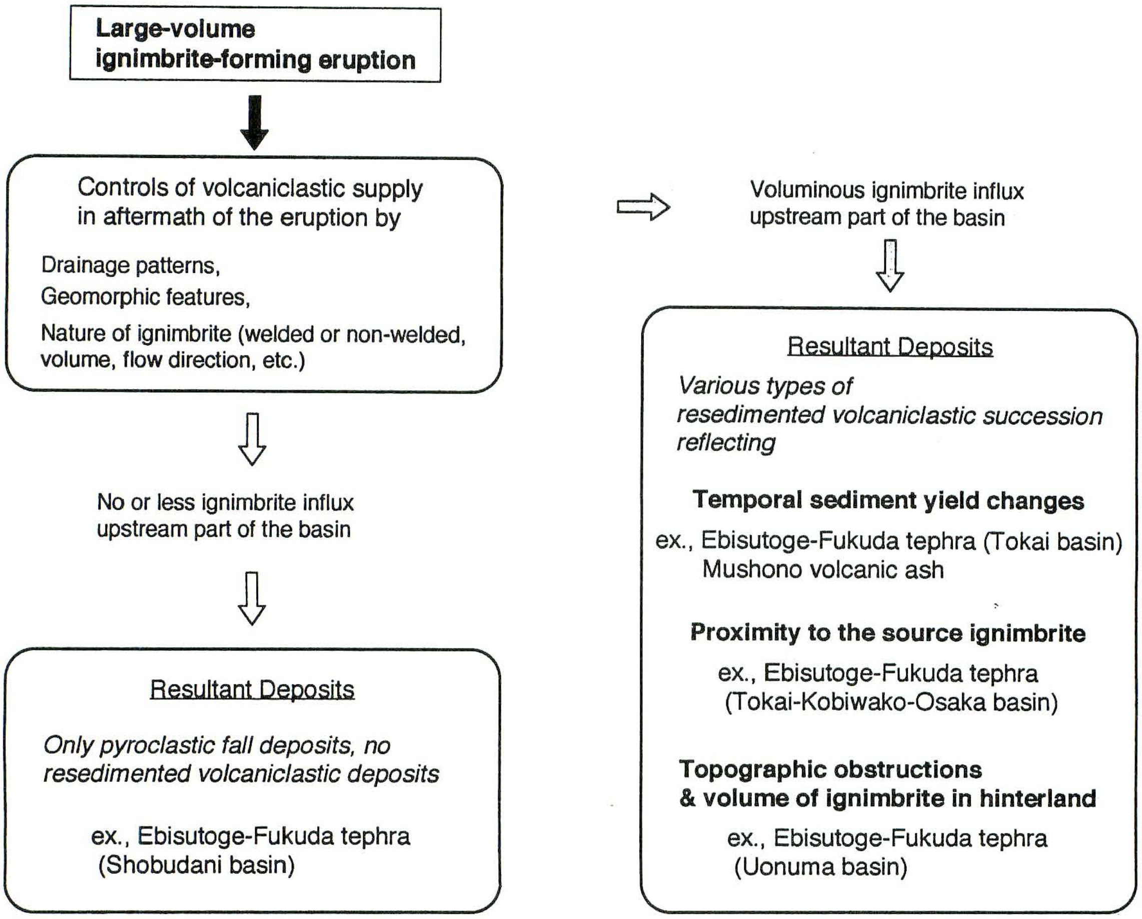

Fig. 9 Controlling factors of volcaniclastic resedimentation induced by large-volume rhyolitic eruptions and resultant deposits.

neglected. Further studies on large-scale volcanism induced resedimentation is necessary to establish the model of resedimentation processes of volcaniclastic sediments and to reveal the controlling factor of resedimentation for the prevention and mitigation of volcanic hazards even at distal locations.

Concluding remarks

In this study, large-scale volcaniclastic resedimentation in fluvial and lacustrine systems of terrestrial settings has been discussed. The Ebisutoge-Fukuda tephra, Plio-Pleistocene boundary, shows large magnitude volcanism and distal fluvial reworking of volcaniclastic material. The Pliocene Mushono volcanic ash layer indicates fluvio-lacustrine deltaic reworking of volcaniclastic debris. In distal volcaniclastic resedimentation with large-volume rhyolitic eruptions, it is considered that most of the distal reworked material was originated from voluminous ignimbrite in a proximal source area rather than from a distal ash-covered landscape or hillslope. Reworking style may have a trend with proximal-distal changes as well as with temporal changes as shown by the concepts of Vessell and Davies (1981), Smith (1988, 1991), McPhie *et al.*, (1993) and others. However, other factors such as topography and drainage patterns affect the resedimentation styles in distal areas (Fig. 9). Duration of reworking of volcaniclastic debris can be estimated less than 10s to 100s of years, and 1000s of years at most in the setting of the Ebisutoge-Fukuda tephra and the Mushono volcanic ash layer. This study also proposes that importance of the volcanic hazard implications in basins distant from the eruptive source. There is high a possibility that large-scale redistribution and resedimentation will be generated if triggered by a large-scale ignimbrite forming eruption. The resedimentation may result in catastrophic floods, burial of reservoirs and filling up of basins, which would ultimately cause damage even at distant areas. It is evident that severe volcanic hazards, by resedimentation of volcaniclastic debris, will spread far and wide and their effects will persist for a longer duration than that by primary eruptive processes.

Nevertheless, the presence of a great deal of ancient rhyolitic volcaniclastic deposits (i.e., widespread tephras) within alluvial successions implies frequent and large volcanic impacts on the alluvial plain on which many people live. Most of the studies on tephras have focused and considered them only as time markers for the tool of classical chronostratigraphy. Not only for the understanding of ancient large-scale volcanism, post-eruptive phenomena, and volcanic hazards in distal place, but also for further high-resolution stratigraphy, we must pay much attention for processes of volcaniclastic sedimentation including primary and reworking ones as well as mechanism of redistribution and resedimentation of widespread volcaniclastic sediments.

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